### WATER PUMPING WITH AC MOTORS AND THIN-FILM SOLAR PANELS

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#### **ABSTRACT**

Water pumping system performance was measured for two different types of thin-film PV panels. The controllers used during the testing converted DC from the solar panels to single or 3-phase AC – depending on submersible motor type. It was found that on similar solar irradiance days, a 3phase AC system with cadmium-telluride panels would pump 80% more water than a single-phase system. However, a 3-phase system with amorphous-silicon panels pumped only 20% more water than a single-phase system due to an improved model controller that was more efficient in single-phase mode. The cadmium-telluride panels were observed to degrade significantly in performance with time. Over 3.5 years the flow rate was observed to decrease by 50%. The 3-phase PV water pumping system with amorphous-silicon panels can pump enough water from a 42 m (138 ft) well to water 164 cattle in the Texas Panhandle.

#### 1. INTRODUCTION

# 1.1 Background

Farmers and ranchers are continually analyzing their options for pumping water for livestock watering, irrigation, and domestic purposes. At the USDA-Agricultural Research Service, Conservation and Production Research Laboratory (CPRL) near Bushland, TX, several wind and/or solar standalone water pumping systems have been investigated. The predominant stand-alone water pumping system (no utility supplied electricity) is to use mechanical windmills. Several experiments have been performed on these systems at CPRL [1-4]. While the longevity of mechanical windmills is unmatched, their frequent and costly maintenance has caused farmers and ranchers to try other methods of

pumping water. The second most popular stand-alone system uses solar-PV panels. These systems can be divided into two categories – DC systems with diaphragm pumps or AC systems with centrifugal/submersible pumps. Research has been performed on these systems at CPRL since the early 1990's [5-8]. While solar-PV systems with diaphragm pumps have been used successfully for shallow (30 meters and less) wells and water requirements less than 3000 liters/day, deeper wells and larger water requirements make solar-PV AC systems with submersible pumps more attractive and are the subject of this paper.

#### 1.2 Cadmium-Telluride Solar Panel Testing.

Research and testing was begun on solar-PV AC systems at CPRL in June 1995 at the request of Southwestern Public Service (SPS) – the local electrical utility. SPS (now XCEL Energy) was considering installing several solar AC systems for pumping water from rural wells that were being supplied with utility electricity. The utility found it very expensive to maintain the distribution lines to these wells and felt it would be more economical to maintain solar AC water pumping systems. Initially the testing was to last 6 months to determine if the solar AC system selected would perform well. The solar AC system selected by XCEL Energy used cadmium-telluride panels, a smart controller, and would use the existing submersible motor (normally single-phase) and submersible pump in the well. The smart controller had several functions including:

- Determining when to cut-in the electrical power from the solar panels to the submersible motor and also when to cut-out the electrical power from the solar panels to the motor.
- (2) Converting the DC power of the panels into single or 3phase AC power for the submersible motor depending on dipswitch settings (inverter function).

- (3) Determining the optimum output power from the controller to submersible motor depending on motor size and pumping depth. For the 1995 controller, a procedure had to be followed by the installer each time there was a change in configuration (motor, pump, pumping depth, and different panel arrangement), but in a later improved 1998 model controller this function was done automatically by the controller.
- (4) Displaying a fault when the solar AC system was not pumping water (underload, overload, etc.).

The system was installed in one day with the help of county extension agents, USDA-ARS personnel, and personnel from the manufacturer of the cadmium-telluride panels. When the panels were installed, the solar array tilt angle was set close to the latitude of Bushland, TX which is approximately 35 degrees north. Starting in the fall of 1995, the tilt angle was set to 45 degrees during the fall and winter and lowered to 25 degrees during the spring and summer. These solar array angles were chosen, so that the tilt angle only differed from the optimum tilt angle by at most 13 degrees [8]. These solar array angles have been consistently set each year except for the year 2000 when the effect of array tilt angle was investigated. The motor/pump configuration tested initially was a 0.56 kW (0.75 hp) 60 Hz single-phase 230 V submersible motor driving a 12-stage 0.56 kW 10 cm (4 in) pump. The initial flow rate was 30 l/min (8 gal/min) for a simulated pumping depth of 42 m (138 ft). After 2 months the flow rate had decreased to 11 1/min (3 gal/min). These thin-film panels degraded rapidly after moisture penetrated into the panel case. The manufacturer made three design changes on the panels by modifying the material on the back of the panel to try to prevent moisture penetration.

#### 1.3 Amorphous-Silicon Panel Testing

After the water pumping performance had degraded 50% from Jan 1998 to June 2001 due to panel degradation, a decision was made to replace the cadmium-telluride thin-film panels with amorphous-silicon thin-film panels. Thin-film panels were selected for several reasons. First, thin-film panels can generate higher voltages than crystalline silicon panels, so fewer panels are required to generate the relatively high voltage (230 V AC) required for off-the-shelf submersible motors. Second, these amorphous-silicon panels had a warranty – only a 10% decrease in optimal performance from rated (43 Watts at 25 degree C panel temperature) after 10 years and a 20% decrease in optimal performance from rated after 20 years. Third, these panels could be installed into the existing solar panel mounting structure.

#### 2. RESULTS

# 2.1 History of Solar AC System Water Pumping at CPRL

A history of the solar-PV AC motor water pumping at CPRL can be seen in Table 1. The bold numbers in the table indicate when a change was made. Testing began in June 1995 with the cadmium-telluride solar panels. In Nov. 1995, due to panel performance degradation, many panels were replaced and the total number was increased from 50 to 60. The single-phase motor was replaced with a 3-phase motor in Mar. 1997. In June 1998 an improved later model controller was installed which was more user friendly. The 60 Hz motor was replaced with a motor rated at 50 Hz in Mar. 1999. In Jan. 2001 two panels cracked from thermal stress that allowed moisture into the panels causing both of these panels to fail. The total number of panels dropped from 60 to 58 at this time. In Nov. 2001 the cadmiumtelluride solar panels were replaced with amorphous-silicon panels, but the system didn't start pumping water until a new improved controller was installed in Apr. 2002. The 50 Hz 3-phase motor was replaced with a 60 Hz 3-phase motor in Oct. 2002, and in Feb. 2003 the 60 Hz 3-phase motor was replaced with a 60 Hz single-phase motor.

#### 2.2 Cadmium-Telluride Panel Degradation

A critical issue with thin-film solar panels is degradation over time. Fig. 1 shows the average monthly water flow rate of the solar AC water pumping system at an irradiance of 1000 W/m<sup>2</sup>. In Dec. 1998 the 60 solar panel arrangement was changed from 12 panels in series and 5 series sets in parallel to 15 panels in series and 4 series sets in parallel. This resulted in an increase in the DC voltage output and a decrease in the DC current output from the solar panels.

# Cadmium-Telluride Panel Degradation Bushland, TX (42 m head, 1000 W/m^2)

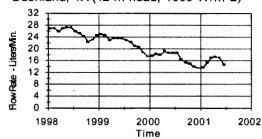


Fig. 1: Flow rate decrease due to thin film solar panel degradation.

This improved the pumping performance about 10%. In Feb. 1999, the 60 Hz motor was replaced with a 50 Hz motor since the frequency of the AC electricity coming from

TABLE 1. SOLAR AC WATER PUMPING TESTING AT THE USDA-ARS LABORATORY AT BUSHLAND, TX WITH CADMIUM-TELLURIDE (CT) AND AMORPHOUS-SILICON (AS) SOLAR PANELS

	Solar Panels				0.56 kW Pump Motor		
Month/Yr	Panel Material	Rated Power/ Panel	# of Panels	Controller Year Model	Phase	Freq. Rating	Simulated Pumping Depth
		(Watts)				(Hz)	(meters)
Jun-95	CT	24	50	1995	1	60	15
Aug-95	CT	24	50	1995	1	60	42
Nov-95	CT	18	60	1995	1	60	42
Jan-96	CT	18	60	1995	1	60	15
Apr-96	CT	18	60	1995	1	60	42
Mar-97	CT	18	60	1995	3	60	42
Jun-98	CT	18	60	1998	3	60	42
Mar-99	CT	18	60	1998	3	50	42
Jan-01	CT	18	58	1998	3	50	42
Apr-02	AS	43	25	2002	3	50	42
Oct-02	AS	43	25	2002	3	60	42
Feb-03	AS	43	25	2002	1	60	42

the controller never exceeded 47 Hz. There was little if any change in performance between the 50 and 60 Hz motors for the cadmium-telluride panels. However, there was a 50% decrease in pumping performance from Jan 1998 to June 2001 due to cadmium-telluride panel degradation.

# 2.3 Single-Phase Vs 3-Phase AC Water Pumping Systems

The effect on pumping performance by switching from a single-phase system to a 3-phase system was very significant for the cadmium-telluride panels (Fig. 2). The irradiation and panel temperature were similar on the two days (Feb. 14, 1997 and Mar. 5, 1997) that were used for the comparison. The increase in the daily water volume using a 3-phase system instead of a single-phase system was 80% due to an increased flow rate, earlier cut-in, and later cut-out of the motor pump. Fig. 3 shows the effect of switching from a single-phase to a 3-phase system for the amorphoussilicon panels – again both days (Feb. 22, 2003 and Feb. 10, 2003) used in this comparison had similar irradiation and panel temperature distributions. Maximum flow rate increased 37% with the amorphous-silicon panels compared to a 50% increase with the cadmium-telluride panels. There was a difference between the cut-in and cut-out for the 3phase and single-phase systems for the amorphous-silicon panels testing, but the difference wasn't as much as with the cadmium-telluride panel testing. The increase in performance of the single-phase system with respect to the 3-phase system for the amorphous-silicon panel testing is due to the improvements made to the later model controller.

#### 1995 Controller (Cadmium-Telluride) 0.56 kW Motors,12 stage pumps,42m Head

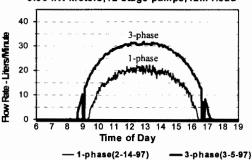


Fig. 2: Effect of using a 3-phase instead of a 1-phase motor system with a 1995 type AC solar controller.

#### 2002 Controller (Amorphous-Silicon) 0.56 kW Motors,12 Stage Pumps,42m Head

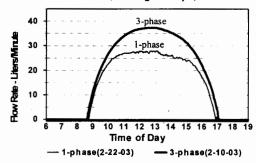


Fig. 3: Effect of using a 3-phase instead of a 1-phase motor with a 2002 type AC solar controller.

The graphs comparing single-phase to 3-phase systems shown in Figures 4, 5, and 6 were obtained by binning several days of data in 100 W/m<sup>2</sup> irradiance bins. Fig. 4 and Fig. 5 shows the frequency and AC power measured for the single-phase and 3-phase systems with the amorphous-silicon panels. The single-phase and 3-phase motors used in

Solar AC (Amorphous-Silicon) 0.56 kW Motor/12 stg pump/42m Head 60 50 4 40 Frequency 30 20 10 400 600 800 1000 1200 1400 0 200 Irradiance - Watts/m^2 - 1-phase Motor - 3-phase Motor

Fig. 4: Measured AC electrical frequency between controller and 60 Hz motors.

Solar AC (Amorphous-Silicon) 0.56 kW Motor/12 stg pump/42m Head 1000 800 AC Power - Watts 600 400 200 0 0 200 400 600 800 1000 1200 1400 Irradiance - Watts/m^2 - 1-phase Motor - 3-phase Motor

Fig. 5: Measured AC electrical power between controller and 60 Hz motors.

# Solar AC (Amorphous-Silicon) 0.56 kW Motor/12 stg pump/42m Head 40 40 30 0 200 400 600 800 1000 1200 1400 Irradiance - Watts/m^2 - 1-phase Motor

Fig. 6: Measured flow rate for solar AC water pumping systems with 1 and 3 phase 60 Hz motors.

this testing were both rated at 0.56 kW, 60 Hz, 230 V. Both used the same pump and simulated pumping depth. The frequency output from the controller varied from 30 to 53 Hz (the higher frequency occurring at the highest irradiance level). The measured AC power output from the controller was virtually the same for both the single and 3-phase systems until the irradiance exceeded 900 W/m<sup>2</sup>. Fig. 6 shows the difference in flow rate for using a single or 3phase system with amorphous-silicon panels. As was seen in Fig. 3, there is an increase in the difference in flow rate between the 3-phase system and the single-phase system for higher levels of irradiance (e.g. the irradiance level peaks at about 1:00 p.m. in Fig. 3). There also is an improvement in flow rate at lower irradiance levels in Fig. 6 and this corresponds with the earlier cut-in and later cut-out of the 3phase system in Fig. 3. The improvement of the 3-phase system at lower irradiance levels is considered due to the single-phase motor requiring more power to overcome the starting torque.

# 2.4 Efficiencies of Solar-PV AC Water Pumping Systems with Amorphous-Silicon Panels

Fig. 7 and Fig. 8 show the various efficiencies measured on the single and 3-phase motors. These graphs represent several days of data that have been binned in 100 W/m<sup>2</sup> irradiance bins. The definition of the various efficiencies are listed below:

- (1) Inverter efficiency = AC power out of controller/ DC power into controller.
- (2) Motor/Pump efficiency = Power in pumped water/ AC power out of controller.
- (3) Panel efficiency = DC power from solar panels/ Sun power incident on panels.
- (4) System efficiency = Power in pumped water/ Sun power incident on panels.

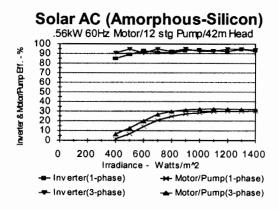


Fig. 7: Inverter and Motor/Pump Efficiency for 1 and 3 phase 60 Hz motors on AC water pumping systems.

#### Solar AC (Amorphous-Silicon) .56kW 60Hz Motor/12 stg Pump/42m Head % 4 Panel & System Eff 3 2 1 0 0 200 400 600 800 1000 1200 1400 Irradiance - Watts/m<sup>2</sup> -- Panel(1-phase) → Sy stem(1-phase) - Panel(3-phase) Sy stem(3-phase)

Fig. 8: Panel and System Efficiency for 1 and 3 phase 60 Hz motors on solar AC water pumping systems.

The measured inverter efficiency of the controller, for both the single and 3-phase systems, averaged 93%. This was 3-5% better than when efficiencies were measured on the older model controller [7]. To estimate DC power, multiply the AC power in Fig. 5 by 1.07. The maximum motor/pump efficiency was 30% for the single-phase motor and 32% for the 3-phase motor. The panel efficiency peaks at 3.7% at an irradiance of 800 W/m² for the single-phase system while the panel efficiency is fairly constant with irradiation at 3.8% for the 3-phase system. The maximum system efficiency was about 0.95% for the single-phase system and 1.15% for the 3-phase system.

# 2.5 <u>Daily Water Volume of Solar-PV AC Water Pumping</u> System with Amorphous-Silicon Panels

Fig. 9 shows how the estimated daily water pumping volume would vary during the year for the single-phase and 3-phase motors with amorphous-silicon panels. The daily water volume increase was about 20% for the 3-phase system compared to the single-phase system. The average irradiance used to estimate these water pumping volumes was collected at CPRL over a four year period (1996-1999). Assuming a beef cow will require 35 liters of water per day in the winter and 50 liters of water per day in the summer [8], this pumping system (twenty-five 43 Watt amorphous-silicon solar panels, 0.56 kW motor/pump, 42 m pumping depth) could water about 134 cattle with the single-phase system and 164 cattle with the 3-phase system. The cost of this system including solar panels, module racks, wiring, controller, motor, pump, and pipe is about \$8000.

# 3. CONCLUSIONS

Panel degradation is evident for both cadmium-telluride thin-film panels and amorphous-silicon thin-film panels.

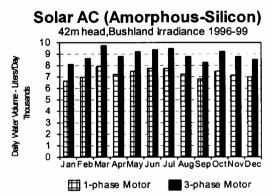


Fig. 9: Measured daily water volume for solar AC water pumping systems with 1 and 3 phase 60 Hz motors.

Panel degradation of cadmium-telluride panels on a solar AC water pumping system caused the performance to decrease 50% over a period of 3.5 years. The twenty-five amorphous-silicon panels were rated at 43 Watts for an irradiance of 1000 W/m², so the output DC power should be 1075 Watts at a panel temperature of 25 degrees C. The DC power has not exceeded 900 Watts at an irradiance of 1000 W/m² on any day (cold or hot), thus it is believed that the panels are 20 % below rated after being exposed to the sun for about 1.5 years.

The increase in water volume by switching from a singlephase to a 3-phase system was 20% with the amorphoussilicon solar panels. This increase in water volume was much less than with the cadmium-telluride panels (80%) and is due to a later model controller being used. The inverter efficiency of this later model controller was also improved and averaged 93% for either the single or 3-phase system. Since the total system efficiency for either system (single or 3-phase) is only around 1%, and the low system efficiency is mainly due to the low panel efficiency (3.5%), a significant improvement in the performance of this AC solar water pumping system requires an improvement in panel efficiency. The 3-phase solar AC system with amorphous-silicon panels will pump enough water to satisfy the water requirements of 164 cattle from a 42 m (138 ft) pumping depth in the Texas Panhandle at a cost of about \$8000.

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